UCRL-JC-133076
PREPRINT

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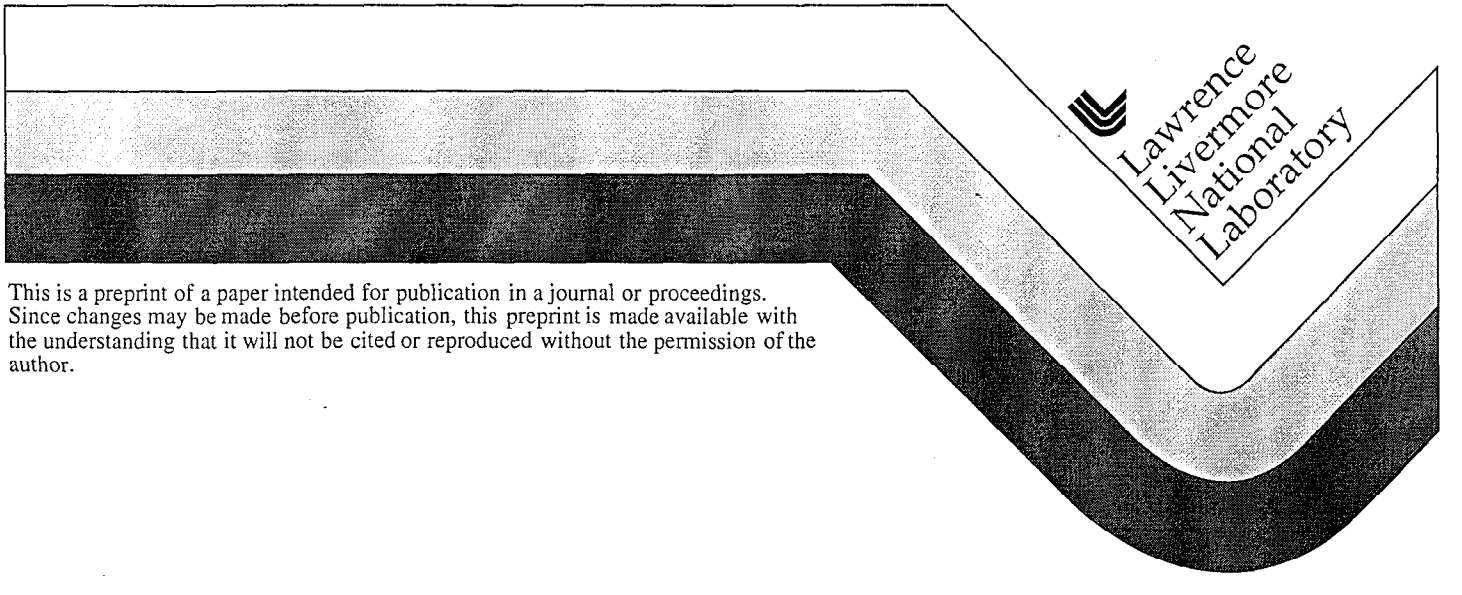
This paper was prepared for submittal to the
11th International Congress of Radiation Research
Dublin, Ireland
July 18-23, 1999

July 1999



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Abstract

PEREGRINE is a 3D Monte Carlo dose calculation system designed to serve as a dose calculation engine for clinical radiation therapy treatment planning systems. Taking advantage of recent advances in low-cost computer hardware, modern multiprocessor architectures and optimized Monte Carlo transport algorithms, PEREGRINE performs mm-resolution Monte Carlo calculations in times that are reasonable for clinical use. PEREGRINE has been developed to simulate radiation therapy for several source types, including photons, electrons, neutrons and protons, for both teletherapy and brachytherapy. However the work described in this paper is limited to linear accelerator-based megavoltage photon therapy.

Here we assess the accuracy, reliability, and added value of 3D Monte Carlo transport for photon therapy treatment planning. Comparisons with clinical measurements in homogeneous and heterogenous phantoms demonstrate PEREGRINE's accuracy. Studies with variable tissue composition demonstrate the importance of material assignment on the overall dose distribution. Detailed analysis of Monte Carlo results provides new information for radiation research by expanding the set of "observables" available in each patient's treatment plan.

Introduction

The PEREGRINE dose calculation system is designed to provide Monte Carlo transport calculations fast enough for day-to-day radiation therapy planning.(1, 2) It operates on low-cost, commodity hardware, enables real time visualization of dose as it is simulated, and completes a full treatment simulation in minutes. The work described here explores the accuracy, reliability, and value of Monte Carlo calculations for linear accelerator-based megavoltage photon therapy.

PEREGRINE System Description

PEREGRINE simulates radiation therapy starting with a set of representative particles randomly sampled from energy, angle, and position distributions determined from offline simulations of the treatment-independent portion of the radiation source. (3, 4, 5) It then tracks each photon, electron, and positron through the treatment-dependent beam delivery system and patient using random numbers, microscopic particle-interaction probabilities, and other standard Monte Carlo transport methods. As each particle interacts, it sets in motion other particles that are also tracked.

Treatment-specific beam modifiers such as collimators, apertures, blocks, multileaf collimators and wedges are modeled explicitly during each PEREGRINE calculation. Each component is described in terms of its physical dimensions, material composition, and density.

The patient is described as a Cartesian map of material composition and density determined from the patient's CT scan. Each CT pixel defines the atomic composition and density of a corresponding transport mesh voxel. Material composition is determined from user-defined CT threshold values. Density is determined from a user-defined piecewise-linear function that describes the CT-number-to-density conversion.

PEREGRINE records the dose deposited by each particle in a uniform Cartesian dose collection mesh that consists of packed dose-collection spheres.

Accuracy and Reliability

Comparisons of PEREGRINE calculations with dosimetric measurements for a Varian 2100C clinical photon beams demonstrates the power of Monte Carlo methods to accurately model the radiation source and predict dose in homogeneous and heterogeneous media. Homogeneous (water) phantom tests primarily assess PEREGRINE's ability to accurately model the beam delivery system. Figure 1A demonstrates PEREGRINE's agreement with ion chamber measurements (Wellhofer IC 10 air-equivalent ion chamber: 6 mm outer diameter, 0.4 mm wall thickness, 3.3 mm active length) for a 20x40 cm, 6-MV beam modified with a 60° standard steel wedge.

Comparisons using heterogeneous phantoms highlight one of the most important advantages of Monte Carlo transport: accurate estimation of doses in areas of electronic disequilibrium. Figure 1B demonstrates PEREGRINE's agreement with diode (Scanditronix photon diode: 0.45 mm thick, 2.5 mm diameter, p-type silicon diode detector) beam-profile measurements for a water phantom with a 2-cm-thick steel heterogeneity, located with its surface at a depth of 3 cm below the phantom surface and extending through half the radiation beam. The photon beam was a 8x20-cm 18-MV beam.). Diode measurements were corrected for over-response to low-energy electrons by normalizing the diode response to IC-10 ion chamber measurements 5 cm off-axis on the no-heterogeneity side of the field. This comparison demonstrates PEREGRINE's accurate prediction of the attenuating effects of the steel slab as well as its effects in areas of electron disequilibrium near its edges.

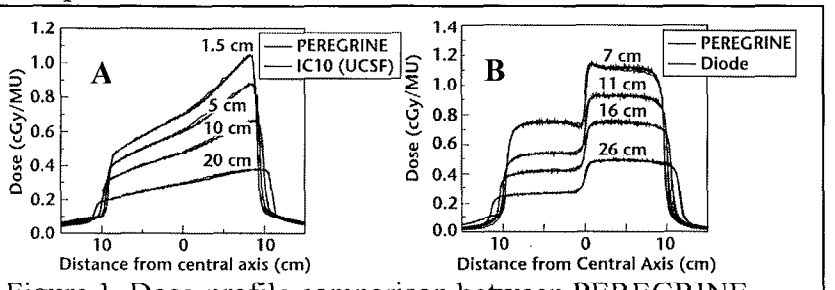

Figure 1. Dose-profile comparison between PEREGRINE calculations and measurements for a 6-MV wedge field incident on a water phantom and a 18-MV open field incident on a water phantom with a steel heterogeneity.

Value of Monte Carlo Calculations

While accuracy is an important part of the contribution of Monte Carlo simulations to clinical radiation therapy, it is only one component of their potential value. Because these calculations represent a true physical simulation of the beam delivery system and patient, Monte Carlo calculations provide new information about how and why dose is being deposited. Examples of this are the influence of material composition, energy spectra of electrons at various points inside the patient, details of how electron transport influences the deposition of dose, and simulation of radiation exiting the patient.

Figure 2 demonstrates the importance of material composition on dose deposition. The case shown here is a four-field treatment of a maxillary sinus tumor, shown as an outline on a representative CT slice. The treatment results in a maximum dose of 68 Gy to the tumor volume. The dose-difference histogram (Figure 2D) for the Gross Tumor Volume (GTV) shows a significant bimodal distribution between doses calculated with and without accurate material assignment. The lower-dose peak in the dose-difference histogram is caused by the presence of bone in the GTV, as is evident by comparing the anatomy revealed through the dose distributions shown (2B and C).

Figure 3 demonstrates how Monte Carlo transport calculations can be used to predict electron energy spectra for particles contributing to dose at arbitrary points in a phantom or patient. Results were calculated with 4x4-cm Varian 2100C photon beams incident on a water

phantom with a 2-cm half-slab bone heterogeneity, located with its top surface at a depth of 3 cm on the water phantom. Figure 3 shows electron energy distributions crossing plane segments centered in the 4x4 cm beam, 1.25 cm off-axis inside and next to the bone heterogeneity, at a depth of 4 cm. These results demonstrate the effect of the bone heterogeneity on the electron energy distribution for both 6- and 18-MV beams. This capability could provide electron source spectra for virtually any plane segment in the body, enabling both microdosimetric calculations and accurate ion chamber signal-to-dose conversion factors.

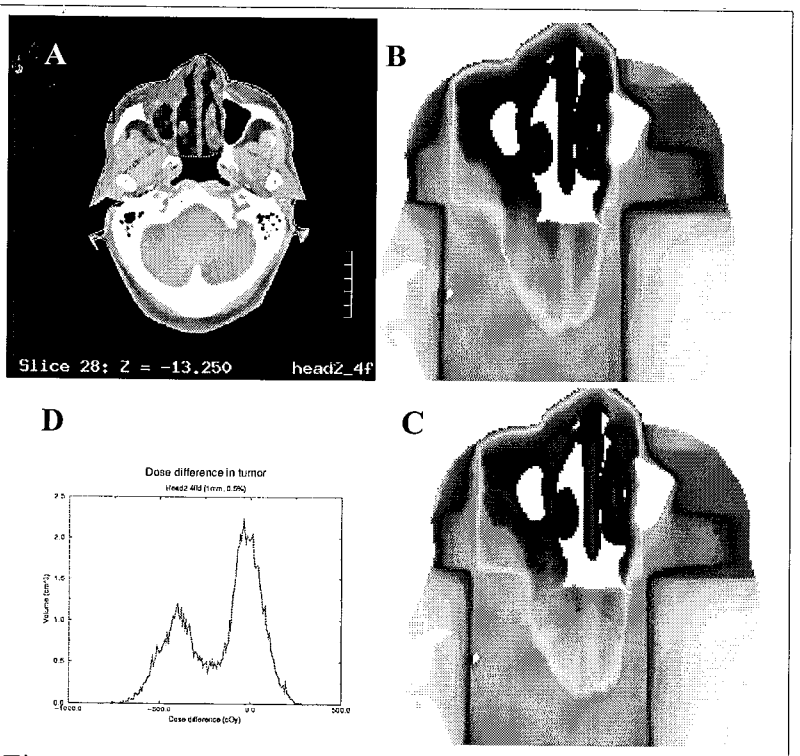

Figure 2. Dose distributions for a 4-field maxillary sinus treatment (CT slice and tumor shown in (A)) for variable-density water (B) and variable density + bone/muscle material assignments (C). The graph (D) shows a histogram of the dose difference observed.

Figure 4 shows a dose-difference distribution, calculated by subtracting a Monte Carlo calculation with electron tracking turned on from one with electron tracking turned off, for the maxillary sinus case shown in Figure 2. The electron dose-difference distribution provides a direct measure of the importance of lateral electron transport to the overall dose distribution. It shows a net loss of dose (dark shading) near the surface and air cavities and a net increase in dose (light shading) related to the presence of bone.

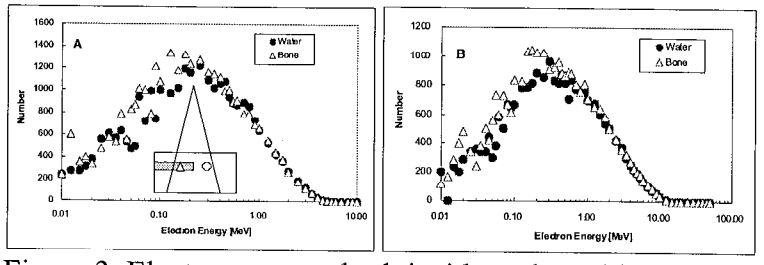

Figure 3. Electron spectra both inside and outside the bone heterogeneity for 6- and 18MV photon beams (A and B, respectively).

Monte Carlo calculations are not only valuable for predicting dose in the patient, but are also useful for predicting the dose exiting the patient. Figure 5 shows an exit dose prediction (dose to a 2-mm steel plate simulating an online image) for a 6-MV Varian 2100C photon beam. By separating the signal from scattered and unscattered photons and analysing the effects of electron transport in the image detection system, we are studying ways to improve the quality of both diagnostic and online images. Hopefully, this will lead to improvements in the quality of online

images used for verification of patient position. We are also developing a system that provides quantitative exit dose information (Figure 5C) that can be compared with online verification systems to help verify that the planned dose was delivered by each field. This verification step is especially important for complex, intensity-modulated treatments.

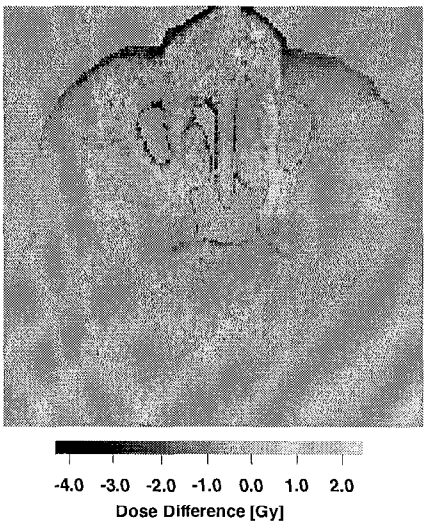

Figure 4. Electron-subtraction dose distribution maxillary sinus treatment.

Conclusions

In this paper, we have used the PEREGRINE dose calculation system as a vehicle to demonstrate the promise of Monte Carlo modeling for radiation therapy. The value of stochastic simulations stems from their ability to use basic, microscopic physical data to provide practical information in arbitrarily complex systems. Their power is limited only by the computational time necessary to complete sufficiently precise calculations and the creativity of their users. The calculations shown here were completed in minutes on hardware designed for clinical treatment planning, and faster computers will allow continued progress. We believe that stochastic simulations will fundamentally change the way we think about all phases of radiation therapy, from basic research to diagnosis and planning to delivery and verification. They will be invaluable tools to translate our understanding of the microscopic world into tangible clinical results.

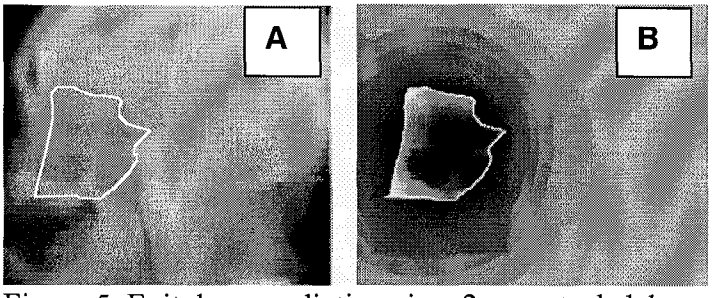

Figure 5. Exit dose predictions in a 2-mm steel slab "detector" at the exit side of the patient for blocked (B) an unblocked (A) fields.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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